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WOOD AND OTHER RENEWABLE RESOURCES

Life cycle assessment of base–load heat sources for district heating system options

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Abstract
Purpose There has been an increased interest in utilizing renewable energy sources in district heating systems. District heating systems are centralized systems that provide heat for residential and commercial buildings in a community. While various renewable and conventional energy sources can be used in such systems, many stakeholders are interested in choosing the feasible option with the least environmental impacts. This paper evaluates and compares environmental burdens of alternative energy source options for the base–load of a district heating center in Vancouver, British Columbia (BC) using the life cycle assessment method. The considered energy sources include natural gas, wood pellet, sewer heat, and ground heat.

Methods The life cycle stages considered in the LCA model cover all stages from fuel production, fuel transmission/transportation, construction, operation, and finally demolition of the district heating system. The impact categories were analyzed based on the IMPACT 2002+ method.

Results and discussion On a life-cycle basis, the global warming effect of renewable energy options were at least 200 kgeqCO2 less than that of the natural gas option per MWh of heat produced by the base–load system. It was concluded that less than 25% of the upstream global warming impact associated with the wood pellet energy source option was due to transportation activities and about 50% of that was resulted from wood pellet production processes. In comparison with other energy options, the wood pellets option has higher impacts on respiratory of inorganics, terrestrial ecotoxicity, acidification, and nutrification categories. Among renewable options, the global warming impact of heat pump options in the studied case in Vancouver, BC, were lower than the wood pellet option due to BC's low carbon electricity generation profile. Ozone layer depletion and mineral extraction were the highest for the heat pump options due to extensive construction required for these options.

Conclusions Natural gas utilization as the primary heat source for district heat production implies environmental complications beyond just the global warming impacts. Diffusing renewable energy sources for generating the base–load district heat would reduce human toxicity, ecosystem quality degradation, global warming, and resource depletion compared to the case of natural gas. Reducing fossil fuel dependency in various stages of wood pellet production can remarkably reduce the upstream global warming impact of using wood pellets for district heat generation.

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1 Introduction

In British Columbia (BC), energy used in the residential and commercial (including commercial and institutional buildings, and public administration) sectors account for about 32% of the total energy consumption in the province (Statistics 2009). Cuddihy et al. (2005) reported that 80% of the energy in the residential sector and 60% in the commercial sector are used for space heating and hot water production, which translates to about 22% of the total energy consumption of the province in 2007. Natural gas (44%) and electricity (40.4%) are currently the two dominant energy sources used in the residential and commercial sectors in BC.

Increased awareness on environmental burdens of energy consumption has increased the number of governments' stimulating plans towards implementing more efficient energy production systems. The BC government is interested in increasing the number of renewable energy portfolios in the basket of primary energy sources in the province. Along with other energy intensive sectors, residential and commercial sectors have also been exploring opportunities for more efficient and renewable based energy producing systems in the recent years (Ministry of Energy, Mines and Petroleum Resources 2009).

One of the renewable energy concepts for providing domestic hot water and space heating is the development of district heating centers. These centers produce hot water or steam for space heating and/or domestic hot water requirement of several buildings. While various renewable and conventional energy sources such as natural gas, ground-based heat, sewer heat, biomass, and solar collectors are available for consideration, many stakeholder groups involved in the development of such projects are interested in choosing the feasible option with the least environmental impacts.

The life cycle assessment (LCA) method has been widely used to study the environmental burdens of energy produced from various renewable and non-renewable sources. Depending on the scope of the LCA study, life stages of the energy production system may include all or part of: (1) fuel production and transportation to the plant, (2) facility construction, (3) facility operation and maintenance, and (4) dismantling (Mann and Spath 2001).

Mann and Spath (2001) carried out a study on life cycle assessment of biomass co-firing in a coal-fired power plant when 5% and 15% of the heat input was replaced by wood residues (waste wood, mill residue, urban wood residue). The life cycle inventory included all stages from fuel preparation (surface coal mining and wood residue acquisition) to material production, manufacturing of co-firing related equipment, coal and biomass transportation, grid electricity production in upstream processes, and the avoided processes of wood residue mulching and landfilling. It was concluded that in terms of MWh of electricity produced by the plant, co-firing reduced airborne emissions (CO_2, SO_2, NO_x, non-methane hydrocarbons, particulates, and carbon CO), total system energy consumption, resource consumption (non-renewable fuel consumption and limestone equivalent), and solid waste generation.

The life cycle assessment of willow energy crop with wood residue co-fired at 5% and 10% energy input rate in a coal-based power plant demonstrated reductions in many of the environmental impacts of the facility (Heller et al. 2004). The incremental life cycle environmental impacts of avoided coal surface mining, combustion and embraced biomass production, cultivation, transportation, and facility modification were estimated. It was shown that electricity generation from willow biomass was nearly greenhouse gas (GHG) free (40–50 kg CO_2/MWh_e). Also, co-firing of willow/wood residue reduced SO_2 and NO_x.

The life cycle environmental impacts of integrated gasification combined cycle (pressurized fluidized bed) for power generation using poplar biomass was investigated by Rafaschieri et al. (1999). The energy and raw material consumption, and polluting emissions from biomass production (nursery, short rotation forestry, plantation, harvesting), processing and transportation to the plant were included in the life-cycle inventory. It was concluded that the use of chemicals and fertilizers during the biomass production phase caused the most negative environmental impacts associated with power generation from poplar biomass. Also, utilization of air as oxidizer during the gasification process caused two to seven times less environmental impacts than the case of oxygen gasification. In order to reduce the life cycle environmental impacts of the process, Rafaschieri et al. (1999) suggested optimizing the applied fertilizer and biological antiparasitic solutions rate based on the biomass yield. In this study, the life cycle inventory did not include power generation, facility construction and dismantling/demolition.

Hondo (2005) developed the life cycle greenhouse gas emissions of nine power generating systems including coal-fired, oil-fired, liquefied natural gas (LNG)-fired, LNG-combined cycle, nuclear, hydropower, geothermal, wind power and solar–photovoltaic (PV). The life stages included: (1) plant construction and equipment production, (2) fuel acquisition, processing, and transportation (in case of fossil fuels and nuclear), geothermal wells drilling (for both exploration and production wells of the geothermal option), (3) facility operation, (4) storage, disposal, or decommis-

sioning (nuclear) of waste. The ranking of the considered options from the best to the worst in terms of GHG emissions (kg_{eq} CO_2 per MWh_{el}) was as follows: hydro (11), geothermal (15), wind 400 kW type (20), nuclear with fuel recycling (22), nuclear without fuel recycling (24), PV with a-Si panels (26), PV-p-Si panels (53), LNG-CC (518), LNG-fired (608), oil-fired (742), coal-fired (975). All the GHG emissions attributed to renewable sources were due to indirect emissions, while for fossil fuel sources, direct CO_2 emissions caused the majority of the impacts.

Zhang et al. (2010) studied and compared the life cycle emissions (GHG, NO_x, and SO_x) of two coal generating stations (co-fired with wood pellets) and a natural gas combined cycle plant in Ontario, Canada. The considered life cycle stages in this study included fuel production, transportation activities, and facility operation. The material and energy inputs required for facility construction, dismantling and equipment manufacturing of energy systems were not considered. It was presumed that these activities had lower life cycle environmental impacts than the operation of the facility. The results of this study showed that the greatest GHG reduction levels per kWh of electricity generated could be achieved by 100% utilization of wood pellets in a coal generating station. This scenario could reduce the GHG emissions of the facility by 91% and 78% of the current levels of coal fired and natural gas fired facilities, respectively. Also, replacement of coal with wood pellets would reduce NO_x and SO_x emissions of the facility by more than 40% and 75%, respectively.

Jungmeier et al. (1998) studied the life cycle environmental burdens of a 1.3 MW_{el} biomass combined heat and power plant that generated 4,700 MWh of electricity and 29,000 MWh of district heat annually in Austria. The life cycle stages included in the study were plant construction, wood fuel preparation (cultivation and harvesting, transportation, processing, storage), plant operation, and dismantling. They concluded that a specific life stage was the main contributor to each impact category. For example, the plant construction phase was the main contributor of CO_2 emissions; the plant operation stage generated the majority of CO and NO_x emissions; and the dismantling phase caused most of the soil emissions.

Eriksson et al. (2007) compared the life cycle environmental impacts of a district heating system in Sweden considering alternative scenarios on fuel, heat only or combined heat and power, and waste management. The functional unit of the LCA was MJ of district heat produced by different scenarios. Based on various impact assessment methods, they concluded that incinerating the biomass in a combined heat and power plant would be more favorable than dumping it in the landfill.

In this paper, the environmental impacts of renewable and non-renewable energy source options for the based load of a district heating center in Vancouver, BC, Canada are evaluated and compared. To the best of our knowledge, this is the first study in Canada evaluating the life cycle environmental impacts of energy source options for a district heating system.

2 Goal

The primary goal of this study is to evaluate and compare the performance of four heat source options for the base–load system of a district heating center in Vancouver, BC, Canada, using the LCA methodology.

The considered district heating center provides hot water and space heating for residential and commercial buildings in a community in Vancouver. It consists of a 10 MW_{th} peaking/backup natural gas boiler, which provides 40% of the annual energy demand, and a 2.5 MW_{th} base–load system, which operates mostly at full capacity during the year to supply 60% of the annual heat demand. Four energy source options of natural gas, wood pellets, sewer heat, and geothermal heat are considered as possible energy options for the base–load system. In order to investigate the decision making process of the heat source option for the district heating center, Ghafghazi et al. (2009a) identified various stakeholder groups, extracted the decision criteria for the stakeholder groups, and used the PROMETHEE II method in order to rank the energy source options. They observed that concerns over environmental impacts of various energy options affect the aggregate decision outcome of the stakeholders. The economic feasibility of the aforementioned four energy source options for this district heating system was studied in Ghafghazi et al. (2010). The results of this study showed that in terms of cost per MWh_{th} of produced heat, the natural gas option was the most economic one. Among renewable options, the wood pellets grate boiler technology was the most economical one with comparable produced heat cost to that of the natural gas; while the cost of heat produced by the heat pump options of sewer heat recovery and geothermal was more than 10% higher than that of the natural gas due to their high initial investment requirements. The current study considers the same district heating center and investigates the life cycle environmental impacts of various energy options. Table 1 lists the specifications of the base–load system considered in the LCA study.

The choice of the functional unit for allocating the environmental impacts of an energy plant would significantly affect the life cycle results (Jungmeier et al. 1998). In this study, the functional unit is "1 MWh_{th}" of thermal energy produced at the district heating center by the base–load system.

Table 1 Specifications of the base–load system considered in the LCA (source: Ghafghazi et al. 2009)

Base–load system specification	Value
Base–load capacity (MW_{th})	2.5
Service life (years)	25
Produced heat during life time (MWh_{th})	486,625
Heat source alternative (efficiency/COP[a])	Technology
Natural gas (82%)	Low- NO_xboiler
Wood pellet (75%)	Moving grate boiler[b]
Sewer heat (3.5)	Sewer heat pump
Geothermal (2.5)	Geothermal heat pump

[a] Coefficient of performance for heat pump options.

[b] With electro static precipitator for flue gas cleaning.

3 System boundaries

The infrastructure required for a district heating system includes the energy center, main grid and auxiliary components, trench works, service pipes, buildings, and dwelling components. The energy center along with the dwelling components such as exchangers are the main contributors to the overall environmental footprints of a district heating system, contributing from 40% to more than 90% in all the environmental impact categories (Oliver-Solà et al. 2009). In this paper, the energy center of the district heating system is the focus of the study.

Those components of the district heating center that would be the same for all options have been excluded from the study. This exclusion includes: the 10 MW_{th} peaking/backup system, energy center office and parking area, hot water pump station, and any required building, equipment, piping, etc. that would not change if alternative options were considered.

The LCA in this study covers all life stages of (1) facility construction, (2) fuel/electricity production and transmission to the facility, (3) facility operation, and (4) dismantling of the facility. Energy and materials used for production of construction materials and equipment as well as energy requirement and wastes from dismantling and recycling processes are incorporated into the LCA model based on rough site specific estimates to evaluate the LCA impact of these phases. Land use, occupation, and disturbance factors were not included in the LCA analysis. Emissions from operating each piece of equipment are calculated. The entire LCA of manufacturing each piece of equipment, such as LCA of manufacturing trucks or trains used for transportations, falls beyond the scope of this study. This omission is consistent with the LCA practices that quantify energy, raw material, and emissions of the entire life cycle of a product (Vigon et al. 1994).

4 Life cycle inventory data and assumptions

The life cycle inventory (LCI) of different energy options was established using different data sources including site specific data, published data, and published databases. Based on the availability, the inventory data that represented the considered processes in the case study in BC the best were used in the LCA model. Therefore, the priority in selecting a dataset for life cycle processes in the model was as follows: (1) British Columbia specific data, (2) Pacific Northwest data, (3) North American data, and (4) modified European database[1] (Frischknecht et al. 2005).

The energy source options for the district heating base–load system include: (1) natural gas, (2) wood pellet, (3) sewer heat, and (4) geothermal heat. Electricity is the primary energy source for running the heat pump of the sewer heat and geothermal heat exchange systems. Table 2 summarizes primary specifications of the energy sources considered for the aforementioned options. The general life cycle stages that have been considered in this study for the base–load system of the district heating center include: (1) primary fuel production/electricity generation, (2) fuel/electricity transmission to facility, (3) facility construction, operation, and dismantling/demolition. These life cycle stages and the sources used for development of the respective inventory for the natural gas, wood pellet, and heat pump (sewer heat and geothermal heat) options are depicted in Fig. 1.

4.1 Fuel production

4.1.1 Electricity

In addition to being the primary energy source for sewage and geothermal heat pumps, electricity is an important input for processes included in the LCA study. The inventory associated with electricity is dependent on the production profile of each region. The electricity generation profile in British Columbia has been: 94.2% of hydro generated electricity (14.1% run-of-river hydropower, 80.1% reservoir hydro power plant), 5.7% natural gas power plants, and 0.1% from other sources (petroleum sources, biomass; St Lawrence 2007). Emission factors considered in the inventory of hydro power include CO_2, SO_2, and NO_x

[1] Ecoinvent v1.2 is a European database provided in the Simapro software. In this study, Ecoinvent database has been adopted by incorporating North American and case specific inputs into Ecoinvent; exception is the case of major equipment supplied from Europe where the Ecoinvent database is used unchanged.

Table 2 Primary specifications of heat source options for the district heating center

Energy source	Specification	Value
Electricity	Hydro	94.2 (%)
	Natural gas	5.7 (%)
	Others (petroleum, biomass, etc.)	0.1 (%)
Natural gas	Density	0.7 (kg/m^3)
	Higher heating value	10.7 (kWh/m^3)
Wood pellets	Density	590 (kg/m^3)
	Higher heating value	5.28 (kWh/kg)
	Moisture content	8 (*wt* %)
	Ash content	0.5 (*wt* %)

obtained from Gagnon et al. (2002) and particulate emissions from Koch (2000). The CO_2 emissions from hydro power generation are from the flooded biomass and decay (Gagnon et al. 2002). The emission factors for natural gas and other sources of generated electricity are obtained from Franklin database (Norris 2004).

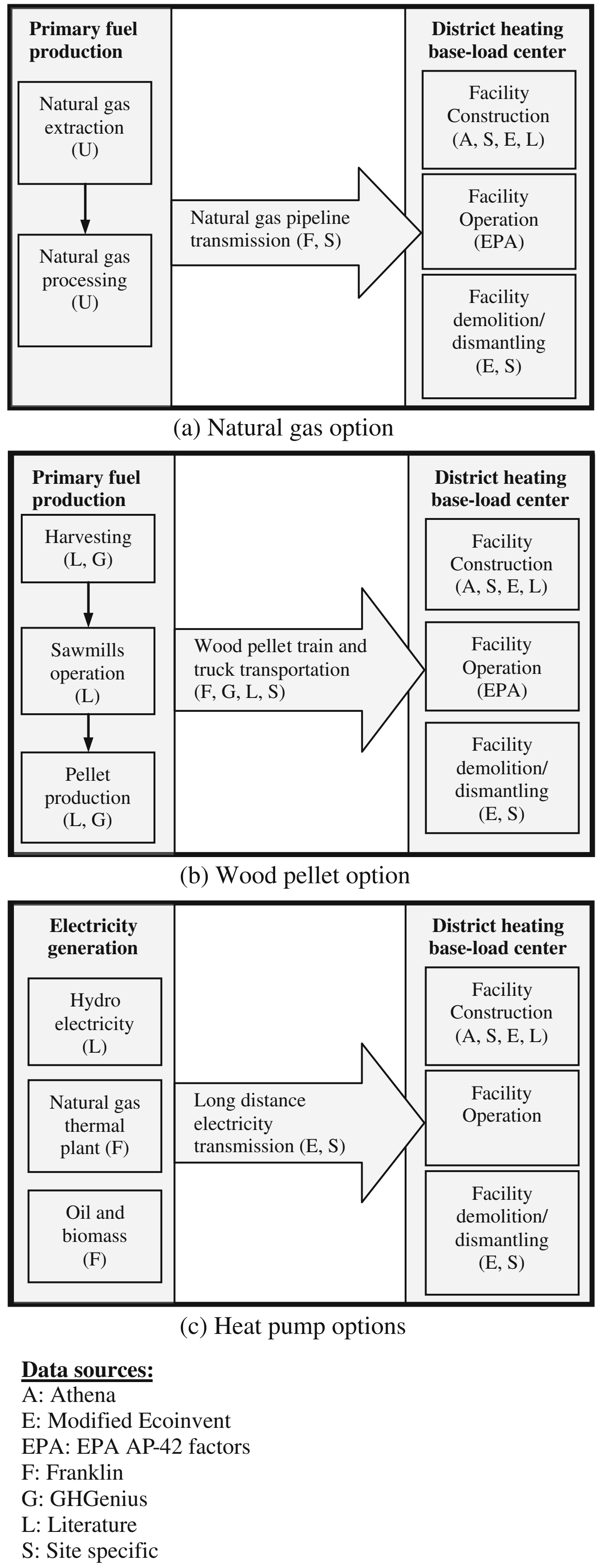
4.1.2 Natural gas

The life cycle of natural gas production and transmission to the district heating base–load system starts with natural gas extraction. Natural gas is commonly co-extracted with crude oil and due to its hydrogen sulfide content is referred to as "sour" gas. In order to obtain marketable natural gas, processing is required to remove heavier hydrocarbons of ethane, butane, propane (liquefied petroleum gasses), water vapor, carbon dioxide, nitrogen (to increase heating value), and hydrogen sulfide ("sweetening"). The natural gas processing mainly results in energy consumption and air borne emissions of fugitive methane, sulfur dioxide, benzene, toluene, ethylbenzene, and xylene (US LCI Database Project 2004a). Since natural gas processing plants are located in the proximity of the extraction sites, it is assumed that transportation between extraction and processing is negligible.

4.1.3 Wood pellets

British Columbia produced over 1.3 million tons of wood pellets in 2009; over 90% of which is currently exported overseas for heat and power production purposes (Government of BC 2010). Wood pellets are categorized as a bio-energy source with zero net CO_2 emission during combustion.

Currently in BC, wood pellets are produced from stem wood sawdust received from sawmills. Therefore, the life cycle of wood pellets starts from harvesting trees for lumber production. The average energy consumption for



(a) Natural gas option

(b) Wood pellet option

(c) Heat pump options

Fig. 1 Life cycle flowchart of the district heating base–load centers

harvesting activities in Western Canada is 7.1 l of diesel fuel per m^3 of harvested wood (Sambo 2002). This average includes planning and layout development, road construction, logging, hauling, camping, silviculture, and also average log transportation to the sawmill. The harvesting regime in this region has been 17% thinning and 83% clear cut (Niemann 2006).

The water and energy consumption and air and soil emissions for sawmill operation in the Pacific Northwest region are obtained from (Milota et al. 2005) and is allocated on a mass basis to the sawdust portion of sawmill byproducts which is used in wood pellet production. Sawmill operations on harvested logs would on average yield 8% bark, 1% hogfuel, 7% sawdust, 27% chips, and 57% lumber on a mass basis. The average density of logs is 500 kg/m^3 and it is 200 kg/m^3 for sawdust.

In BC, sawdust is transported on an average distance of 27 km by trucks to wood pellet-producing plants (Magelli et al. 2009) to be used as: (1) wood pellet raw material (1.56 t sawdust/1 t wood pellet) and (2) energy source for the drying phase of wood pellet production (267 kg sawdust/1 t wood pellet) (Mani 2005). The amount of electricity and diesel fuel consumption in a wood pellet plant are also obtained from Mani (2005). Emission factors for sawdust combustion at wood pellet plant is estimated based on EPA emission factors for wet wood residue combustion (Environmental Protection Agency 2003).

In this paper, a key assumption in developing the emission inventory of biomass combustion is that the net CO_2 emissions resulting from sawdust or wood pellets combustion is zero (Johnson 2009). It should be noted that this approach, which is based on the biofuels carbon neutrality assumption, is valid for current sawdust and wood pellet production practice in BC. The raw material used for pellet production is the wood waste produced at sawmills that would eventually release its carbon to the atmosphere. The carbon neutrality assumption can be held valid as long as the obtained wood for combustion purposes does not result in deforestation and long term carbon stock change at the forests sites (Johnson 2009) and is obtained either from sustainably managed forests or byproducts of other sustainable forest operations.

4.2 Energy source transmission

Transmission of electricity to the facility has been incorporated in the LCA inventory in terms of electricity loss. The average electricity loss due to high voltage long-distance transmission was considered to be 30 Wh per MWh km (Frischknecht et al. 2005). The weighted average long distance electricity transmission is 750 km based on distances from major electricity generation sites in BC which are located at Peace Region (34% electricity generation contribution, 1,200 km), Columbia Region (31% electricity generation contribution, 600 km), and the Interior and Coastal Regions (35%, various locations from 100 to 1,000 km; Shabani 2009).

The Franklin database (Norris 2004) is used for pipeline transmission of natural gas from an average distanced natural gas inlet station located at Fort St. John, BC, Canada to the district heating system in Vancouver, BC, which is 1,200 km.

GHGenius 3.16c developed by Natural Resources Canada for life cycle assessment of transportation fuels (http://www.ghgenius.ca/) is used to estimate emissions from heavy duty diesel or gasoline engines, truck and train transportations. The average diesel truck fuel consumption has been corrected to 66 l/100 km (Ressaire 2006); this average represents truck fuel consumption with and without a 25-t payload in a tri-axle semi-trailer normally used for such type of transportation.

Transportation of wood pellets to the district heating center for final use includes a series of truck and train transportation and storage. After production, wood pellets are transported to railhead for an average distance of 25 km and then transported over an average distance of 781 km via rail to a port in Vancouver, BC (Magelli et al. 2009). Wood pellet truck transportation is considered as a two-way trip: one-way loaded and one-way commuting back unloaded. Electricity and fuel consumed at the Vancouver port for unloading, storage, and then loading of wood pellets are obtained from Pa (2009) who surveyed Wood pellet Association of Canada. Wood pellets are trucked to the energy center over a distance of 11 km for combustion in a grate boiler for heat generation purpose.

4.3 District heating center construction

The structure of the district heating center is made from reinforced concrete. Emissions and recourse inventories for 30 MPa structural concrete type, which is a common type of structure for building constructions in Vancouver, are obtained from Athena Sustainable Materials (2005). The amount of steel rebar (US LCI Database Project 2004b) on a volume basis is 2% of concrete volume and the density of steel is 7,850 kg/m^3. The energy consumption during facility construction is not included in the inventory. The inventory of steel pipes required for the boiler and exchange houses have been developed based on the US LCI information for galvanized steel sheet production (US LCI database project 2004b) and the North American inputs incorporated in Ecoinvent database has been used for drawing process of pipe production. The required pieces of equipment for different options, such as natural gas boiler, wood pellet boiler, heat pumps, and exchangers, were assumed to be procured in Europe;

therefore, the Ecoinvent database was used to develop the inventory of the equipment. The inventory also includes ocean shipment of the equipment from Europe to Vancouver, BC.

The inventory of wood boiler procured from Europe includes the required auxiliary equipment such as chimney, storage silo, automatic fuel supply, and automatic control. Ocean transportation of equipment is also included for an average distance of 7,400 km between Europe and BC, Canada. The inventory of electro static precipitator (ESP) system on wood boiler is not included.

For the geothermal option, the North American incorporated Ecoinvent database has been used for the drilling and construction activity of a 150 m deep geothermal vertical loop configuration. Major components of the geothermal exchange system are the heat exchanger, heat pump, geothermal wells, and required interconnecting piping between the wells and heat exchangers.

The specifications of the required sewage pump station to redirect, pre-treat and make the sewage useable in the exchangers are site specific. Major components of the sewage heat recovery system include heat exchanger, heat pump, interconnecting piping between treatment equipment and heat exchangers, cooling tower evaporator, and sewage pretreatment unit, which consists of auto cleaning screens, booster pumps, backwash pits, and transfer pumps. Inventory of the mechanical equipment for sewage pump station including screens and pumps were not available to include in the model. Electricity and water used during the operation of the sewage pump station are also included in the sewage pump station inventory.

4.4 District heating center operation

The amount of energy used (fuel and electricity) during the operation of the district heating system and emissions generated from fuel combustion were considered in the LCA analysis. Electricity consumption to run heat pumps of the sewer heat recovery and geothermal options has been calculated based on 3.5 and 2.5 coefficient of performance (COP) for the systems, respectively. The amount of natural gas burned in the boiler to produce 1 MWh thermal energy based on 82% boiler efficiency and 10.7 kWh/m^3 natural gas energy density would be 118.7 m^3. The combustion emissions of a low NO_x natural gas boiler have been obtained from EPA AP-42 (Environmental Protection Agency 2003). The amount of wood pellets required to produce 1 MWh thermal energy based on 75% boiler efficiency and wood pellets energy density of 5.28 kWh/kg would be 253 kg. The combustion emissions for burning dry wood in wood boiler equipped with an ESP has been obtained from EPA AP-42 (Environmental Protection Agency 2003). The emission levels reported in EPA AP-42 for composition of particulates such as alkali and heavy metals or dioxin and furans have been reduced by a factor of 95% as a result of ESP cleaning. The original levels reported in EPA AP-42 do not incorporate flue gas cleaning reduction measures.

4.5 Dismantling

The dismantling process happens after 25-year service life of the district heating center. The inventory of dismantling process for various heat source options have been developed based on the North American inputs incorporated into the Ecoinvent database. It is assumed that construction wastes are dumped in the landfill and metals such as steel pipes are recycled.

5 Life cycle impact assessment

The environmental impacts of all consumed resources and resulted emissions are assessed using the Simapro software (http://www.pre.nl/simapro/default.htm) v7.0. The levels of midpoint categories and endpoint damage indicators are calculated based on the IMPACT 2002+ v2.1 (Jolliet et al. 2003) method. IMPACT 2002+ as suggested by the International Standard Organization (2000) benefits from both classical impact assessment methods, which consider the so-called midpoint categories, and the damage oriented methods, which report the endpoint indicators. Twelve out of 14 midpoint impact categories and four endpoint damage categories and their equivalent indicators which IMPACT 2002+ reflects upon are considered in this study. Land occupation and ionizing radiation midpoint categories were not included in the impact assessment since the associated inventory of these midpoint categories have not been developed in this study.

The midpoint categories of each heat source option considered for the district heating center can be seen in Table 3. The midpoint category values are not readily interpretable to environmental impacts and can be looked at as a comparative tool for environmental performance of alternative options under consideration. The midpoint categories can be classified into three classes based on their impact range: (1) local impacts such as human toxicity and respiratory effects that are related to human health effects, (2) regional impacts such as ozone layer depletion, aquatic and terrestrial impacts, and (3) global impacts including global warming, non-renewable energy consumption, and mineral extraction categories.

The potential risks associated with the local midpoint categories that affect human health are very much depen-

Table 3 Midpoint categories of various heat source options per MWh thermal energy produced at the district heating center

Midpoint category	Unit	Natural gas	Wood pellets	Sewer	Geothermal
Carcinogens[a]	kg_{eq} C_2H_3Cl	0.384	0.278	0.0808	0.0288
Non-carcinogens[a]	kg_{eq} C_2H_3Cl	5.76	0.219	0.267	0.359
Respiratory inorganics	kg_{eq} $PM_{2.5}$	0.256	0.292	0.0165	0.0222
Respiratory organics	kg_{eq} *ethylene*	0.0345	0.0223	0.000102	0.000102
Ozone layer depletion	kg_{eq} *CFC-11*	1.25E-08	0.0000187	0.00122	0.00183
Aquatic ecotoxicity	kg_{eq} *TEG*[b] *water*	36,000	515	1,530	2,390
Terrestrial ecotoxicity	kg_{eq} *TEG*[b] soil	7.45	43.9	15.2	24.8
Terrestrial acid./nutri. [c]	kg_{eq} SO_2	4.68	7.07	0.44	0.59
Aquatic acidification	kg_{eq} SO_2	2.72	0.998	0.149	0.201
Aquatic eutrophication	kg_{eq} PO_4^{3-}	0.00258	0.000101	0.000151	0.000227
Global warming	kg_{eq} CO_2	240	39.4	15.8	24.6
Non-renewable energy	MJ primary	4,390	208	21.1	29.8
Mineral extraction	kg_{eq} iron	0.0271	0.0275	0.0501	0.0528

[a] Human toxicity effect

[b] TriEthylene glycol

[c] Acidification/nutrification

dent on the level and duration of human exposure to the associated toxic substances. For example, direct occupational exposure of human to vinyl chloride has very high risks of angiosarcoma of the liver, but the risk level reduces to negligible when considering the general public's risk of angiosarcoma due to escaping vinyl chloride into the environment from plants carrying this substance in the past (Doll 1988). Thus, the risk of these midpoint categories for each option, despite the overall value, should be identified based on the upstream inventory of the main contributors and whether the risk of human exposure could be high or not. For instance, emissions from a local facility can be seen as long-term human exposure risk for the people living in the vicinity of the facility.

6 Discussion

Comparison of LCA midpoint categories of the four energy options showed that a single energy source option that outperforms other options with regards to all the midpoint categories could not be identified. The natural gas option resulted in higher impacts in global warming, non-renewable energy consumption, carcinogens and non-carcinogens, respiratory organics, aquatic ecotoxicity, acidification, and eutrophication compared to the renewable options.

As shown in Fig. 2, emissions from natural gas combustion during facility operation have remarkable contribution in midpoint categories of carcinogens, terrestrial ecotoxicity, acidification/nutrification, global warming, and non-renewable energy consumption. The carcinogenic effect of the natural gas option is mostly due to molybdenum and VOC emissions found in the flue gas of natural gas combustion during facility operation. Trace elements of copper, cadmium, chromium, and aluminum found in natural gas flue gas combustion account for facility operation contribution to the terrestrial ecotoxicity of this option.

The natural gas extraction phase is the main contributor to non-carcinogens, ozone layer depletion, aquatic ecotoxicity, and aquatic eutrophication categories of the natural gas option. Release of tetrachloromethane during natural gas extraction and also long distance pipeline transmission stages result in most of the ozone layer depleting effect of this process. Natural gas extraction results in waterborne emissions of aluminum and barium (US LCI Database Project, 2004a) which has very high aquatic ecotoxicity effect. Also, the chemical oxygen demand during natural gas extraction is a major contributor to the aquatic eutrophication impact of the natural gas option.

The natural gas processing phase has higher impacts on the two respiratory categories: terrestrial acidification/nutrification, and aquatic acidification. Since the natural gas processing sites are located in remote areas, the respiratory impacts associated with this process present low risk for the general public, but high risk for people living or working in the vicinity of the sites. Sulfur dioxide emission during the natural gas processing phase is the main contributor to terrestrial acidification/nutrification and aquatic acidification impacts of the natural gas option.

Facility construction and dismantling of the natural gas option is the single contributor to the mineral extraction category and results in terrestrial acidification/nutrification effect; the latter is due to aluminum, copper, chromium, and iron used in the manufacturing of the pipes, natural gas boiler, and pipe line transmission.

In comparison with other energy options (see Table 3), the wood pellets option has higher impacts on respiratory of inorganics and terrestrial ecotoxicity, acidification, and nutrification categories. Figure 3 depicts the contribution of different life cycle stages to the mid-category impacts of

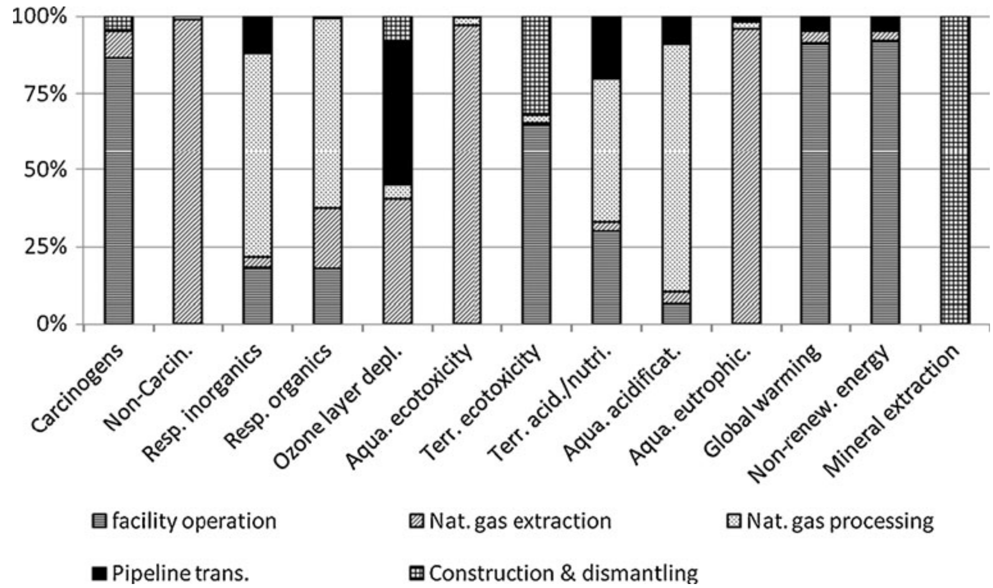


Fig. 2 Contribution (%) of life cycle stages to midpoint effects—natural gas option

the wood pellets option. Emissions from combustion of wood pellets during facility operation are the major contributor to the respiratory effects. The major contributors to the respiratory inorganics category were particulate emissions and nitrogen oxides resulted from wood pellets combustion.

Copper emissions to soil and to a lesser degree to the atmosphere are considered the most toxic factors in the aquatic and terrestrial ecotoxicity midpoint categories. In the case of the wood pellets option, entrainment of copper element in the flue gas and especially bottom ash during sawdust production, pelletization, and facility operation account for majority of the aquatic ecotoxicity effect. Trace elements of heavy metal found in the flue gas and ash of combusted wood during the pelletization process are the most important contributors to the terrestrial ecotoxicity impact of utilizing wood pellets. It is assumed here that pellet-producing facilities do not implement high efficiency flue gas cleaning technologies such as ESPs or baghouses for the sawdust combustion used for the drying phase. It should also be noted that the emission levels reported here for particulate emissions for the wood pellet option does not suggest whether or not the levels of particulate emissions, dioxin, and furans exceed the regulatory limits of the region. The measured particulate emission levels from wood pellet combustion at a district heating facility with the relatively same technology and capacity as considered in this study were in the 55–100 mg/m3 (at 20°C,

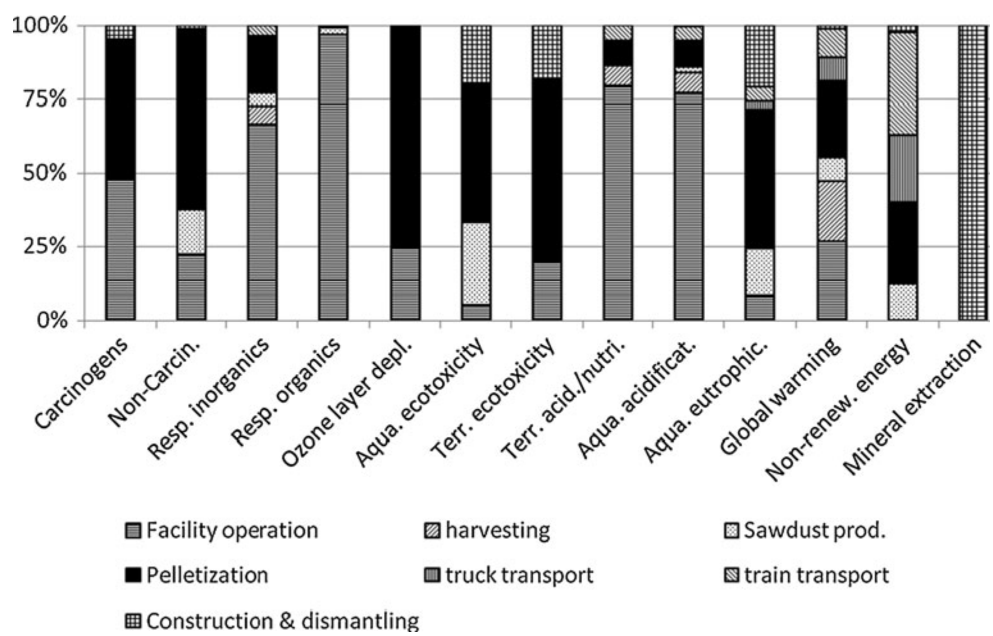


Fig. 3 Contribution (%) of life cycle stages to midpoint effects—wood pellets option

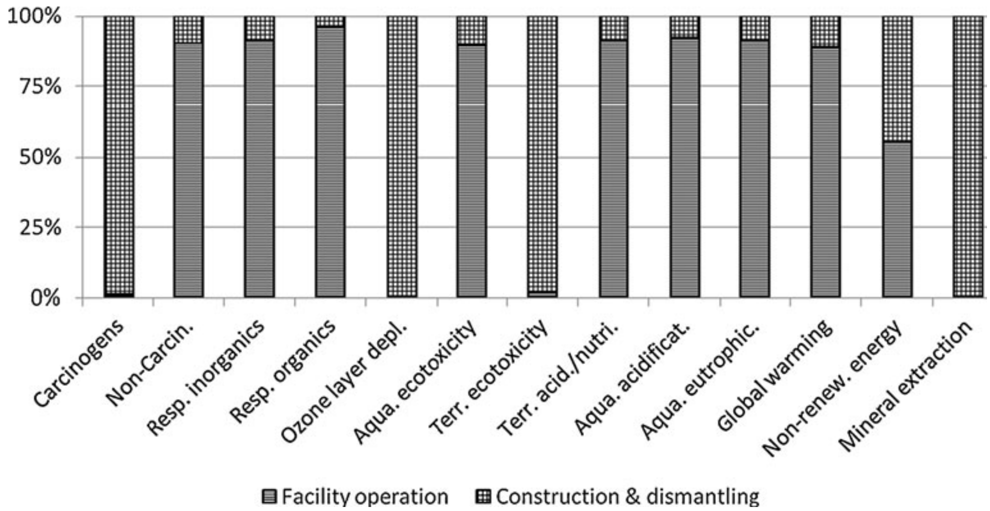


Fig. 4 Contribution (%) of life cycle stages to midpoint effects —sewer heat option

101.325 kPa, dry gas, and 8% O_2) range (Johansson et al. 2003). With the installation of an ESP system with collection efficiency above 90% (Hasler and Nussbaumer 1999), this emission level will be well below the regulatory limits of 18 mg/m3 (at 20°C, 101.325 kPa, dry gas, and 8% O_2) in Vancouver, BC (Metro Vancouver 2008).

Less than 25% of the global warming impact associated with utilization of wood pellets is resulted from fossil fuels used for train and truck transportation of wood pellets to the facility. Combustion of wood pellet as a renewable source does not generate any net CO_2 emission; however, generation of other gas emissions that have global warming impact, such as methane, contribute to global warming impact of wood pellets during facility operation. About 50% of the upstream global warming impact associated with the wood pellet option is due to fossil fuel consumption during harvesting, sawmills operation, and pelletization processes. Such an impact can be mitigated further by replacing fossil fuel based equipment with renewable energy based ones. Although Jungmeier et al. (1998) concluded that CO_2 emissions during the facility construction due to steel and concrete production were higher than those of facility operation and biomass fuel preparation, the results of this study showed that GHG emissions associated with wood pellet production and facility operation exceeded those associated with upstream material preparation for the facility construction phase.

As presented in Figs. 4 and 5, the contribution of various life stages of the sewer heat recovery and geothermal options to the midpoint categories show relatively the same pattern. The geothermal and sewer heat recovery options have the highest impact levels on ozone layer depletion and require higher mineral extraction compared to other alternatives (see Table 3). The facility construction and dismantling phase for both heat pump options is the major contributor to both the ozone layer depletion and mineral extraction effects. The working fluid compound of HCFC used in the heat pump systems (Li et al. 2002) is the major

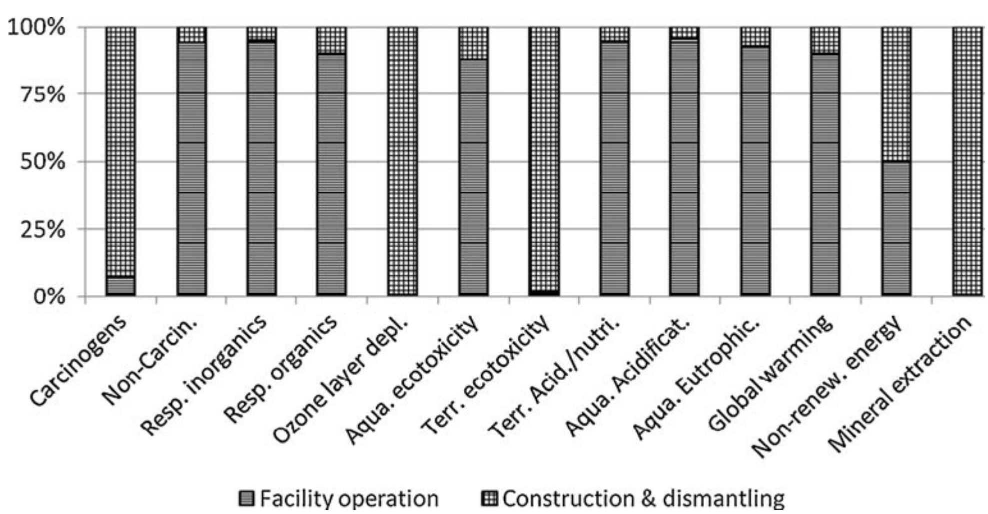


Fig. 5 Contribution (%) of life cycle stages to midpoint effects—Geothermal heat option

contributor to ozone depletion effect of sewer and geothermal options.

For the two heat pump options, facility operation, which includes electricity generation and transmission to the facility, is responsible for major impacts on non-carcinogens, respiratory, aquatic ecotoxicity, acidification, and eutrophication, terrestrial acidification/nutrification, global warming and non-renewable energy consumption categories. These effects for both options are mainly resulted from the fossil fuel generated portion of the electricity utilized by the heat pumps, and hence, emissions leading to these impacts are deemed scattered over various locations of the thermal plants. Facility operation is emission free at the district heating center for the two heat pump options.

The impact assessment results confirm the conclusion driven by Jungmeier et al. (1998) that certain life stages are the main contributors to certain impact categories. For instance, the natural gas extraction and processing stages have higher impacts on aquatic ecosystem quality degradation, while the facility operation stage is the main contributor to the global warming impact. It was also concluded that life cycle impacts associated with construction and dismantling of heat pump options may have notable effect on certain impact categories (see Figs. 4 and 5). This result is in contrast with the assumption made in the study conducted by Zhang et al. (2010) in which life cycle impacts associated with facility operation were deemed to be far more than those of the facility construction phase.

7 Conclusions

In this study, the life cycle environmental burdens associated with utilization of various energy source options to provide the base–load of a district heating system in Vancouver, BC, Canada were studied. The energy sources considered for the base–load system included natural gas, wood pellet, sewer heat, and ground heat. The LCA analysis considered all the life stages of the base–load system: facility construction, fuel/electricity production phase, facility operation, and facility dismantling. The results showed that none of the energy options outperformed other alternatives considering all the midpoint impact categories.

It was shown that utilizing renewable energy options instead of natural gas would result in more than 200 kg_{eq} CO_2 emissions reduction per MWh of heat produced at the district heating center. The results for sewage heat and geothermal heat options are dependent on the efficiency (COP) of the systems and also electricity generation profile of the region. In the current situation in BC, majority of electricity is low carbon hydro generated. In other words, if the share of fossil fuel generated electricity increases in the electricity generation profile of the region, the results would change. The green house gasses generated during wood pellet production will also be higher if non-renewable energy sources, such as natural gas, were used. Thus, in order to limit the upstream global warming impacts associated with the wood pellet production, new pelletizing facilities constructed in the region should adopt biomass based heat generation equipment instead of fossil based counterparts.

The results of this study also show that primary resource depletion and global warming effects are not the only environmental impacts associated with utilization of natural gas as the heat source, but also human toxicity effects due to natural gas combustion during facility operation and ecosystem quality degradation (especially aquatic ecosystems) at natural gas processing and extraction sites are major environmental issues associated with this option. Mitigation of natural gas extraction effects on the regional ecosystem through alternative processes can be studied further.

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